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Review

Revisiting harmful algal blooms in India through a global lens: An integrated framework for enhanced research and monitoring

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SUMMARY

Harmful algal bloom (HAB) events substantially impact human and aquatic ecosystem health and the global blue economy; hence, a concerted effort is required to advance our understanding of HAB ecology to better inform monitoring and mitigation measures. Here, we highlight the current state of HAB research and monitoring in India, where ∼17% of the human population resides in the vicinity of its long coastline and is dependent on the sustainable blue economy. Through the lens of established programs from countries across the globe, we identify existing gaps and highlight four broad areas for focusing future efforts: (1) the development/employment of novel technologies for HAB research and monitoring; (2) the need for integrated observation networks and a coordinated effort across different central/state agencies and research institutes; (3) clinical studies on human health effects; and (4) public outreach and citizen science initiatives to increase awareness on this topic, including policy level interventions.

INTRODUCTION

Aquatic phytoplankton are photoautotrophs or mixotrophs, with an estimated contribution of ∼50% to global photosynthesis.[1] As the base of most aquatic food chains, they play a crucial role in ecosystem health, while also being major contributors to carbon sequestration and global biogeochemical cycles.[2] Therefore, phytoplankton are also key players in the context of climate processes. The abundance, distribution, and species composition of phytoplankton are dependent on a complex interplay of diverse factors, including but not limited to light and nutrient availability, temperature, salinity, stratification, tidal regimes, and flow and turbulence across different temporal and spatial scales.[3,4] Their inherently nonhomogeneous distribution can manifest itself into phenomena such as plankton blooms and thin layers—vertically limited dense patches of high plankton abundance—where favorable conditions lead to rapid and exponential population growth.[5]

Phytoplankton (or algal) blooms refer to events where the phytoplankton biomass is elevated to concentrations exceeding typical levels, often, but not always, over short timescales.[3] Many, but not all, algal blooms, are classified as harmful based on their direct or indirect impact on human and marine ecosystem health,[6] due to one or more of the following reasons: (1) generation of toxins that can affect humans and/or other organisms; (2) depletion of oxygen in the water column, causing anoxic/hypoxic conditions, leading to fish and marine mammal kills; (3) clogging and/or damage of fish or marine invertebrate gills leading to their mortality; and (4) sunlight blockage due to dense surface aggregates, leading to seagrass/other benthic flora mortalities. The duration, frequency and severity of harmful algal bloom (HAB) events in freshwater, estuarine, and marine environments, adjusted for monitoring/sampling differences across geographical locations, show variable and region-specific trends.[7] In India, reports of HAB events have clearly increased in recent decades,[8,9] but it is currently unclear if this is part of the perceived overall global increase, which Hallegraeff et al.[7] attribute to enhanced monitoring approaches and awareness.

The formation and sustenance of HABs is driven by a diverse set of physical, biological, and environmental factors,[10] which in many cases is correlated with anthropogenic inputs and climate change.[1] HABs can severely impact human and aquatic ecosystem health, as well as local economies.[11–13] Consequently, a concerted effort is required to advance our understanding of HAB ecology to better inform monitoring and mitigation measures as evidenced by several international programs such as Global Ecology of HABs[11] and EURO HAB.[14] A significant portion of existing research on HABs comes from a handful of countries or regions, including but not limited to, the United

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States and Europe, while much remains to be addressed in other geographical areas, particularly in regions associated with the "Global South."

Here, we consider the case of India, a rapidly growing global player, with a 1.4+ billion population, where over 200+ million citizens depend on the sustainable blue economy. HABs, with their deleterious impacts on marine ecosystems, including fish, can substantially impact the blue economy at local and regional scales. An overview of historical algal bloom records and the mechanisms, causes and impacts of HABs in coastal Indian waters are provided in two comprehensive reviews by D'Silva et al.[15] and Thomas et al.[9] However, both articles only briefly touch upon recommendations for future research and strengthening existing monitoring capabilities. While Bhat and Matondkar[16] provide an interesting perspective and several insightful recommendations, rapid developments in observational capabilities and research tools over the past couple of decades favor another fresh outlook on the issue. Our paper aims to complement these efforts by only lightly touching on material already covered, while focusing primarily on aspects that were not included in these publications and is organized as follows. We begin with a summary of historical HAB records in India, followed by a short comment on the importance of tackling HAB issues in the context of the United Nations Sustainable Development Goals (UNSDG). In the remaining sections, the discussion revolves around potential avenues to enhance our understanding of Indian HABs and establish a robust scientific program for sustained measurements with the ability to boost the blue economy. This is discussed in the context of existing HAB monitoring and research programs from different regions around the world, which are interspersed throughout the text. While we have attempted to draw aspects from diverse regions, there is a slight bias toward the US, primarily due to the strong historical funding, government-level intervention, and policy initiatives that make it a leader in this field. At the same time, care has been taken to ensure the proposed ideas are practical within the Indian framework. While our focus is India, most of the ideas are equally applicable to other countries in the Global South. Freshwater species are only briefly considered here, and we restrict most of our discussion to coastal waters. HABs in inland waters (lakes, ponds, reservoirs, etc.) can be equally important,[17] but fall beyond the scope of this current effort. Several studies over the last decade have shown the capability of molecular tools for rapid detection of HABs in coastal water and beyond.[18–21] Molecular and chemical approaches for HAB analysis, including mechanisms linked to HAB formation are not discussed here; similarly, HAB control and mitigation efforts/studies are also beyond the current scope.

BRIEF HISTORY OF HABs IN INDIA

To the best of our knowledge, the earliest modern Indian reference to "red water" is from the tidal pools of Bombay (currently Mumbai), Maharashtra, documented by Carter,[22] who attributed it to the presence of a newly described dinoflagellate species, *Peridinium sanguineum* (current name: *Glenodinium sanguineum*). In the same report, Carter also refers to an eyewitness record of changes in seawater color and associated fish kills from Porebunder (now Porbandar), Gujarat in 1849. The next detailed Indian scientific record, typically attributed in earlier works as the first that fits the modern definition of HABs, is from the coast of Mangalore (now Mangaluru), Karnataka, in the Arabian Sea in November 1908.[23,24] Similar observations were made in Calicut (Kozhikode), Kerala, in November 1912, which Hornell[24] describes as caused by "brownish yellow Euglenids," identified to most likely be the raphidophyte, *Chattonella marina*, by later studies.[25] Importantly, Hornell stresses the fact that these recurring incidents, while not officially recorded, were well known to local fisherfolk.

Since these early observations, as of October 2022, a total of 218 HAB events have been documented in Indian waters.[26] The fact that ~65% (141) of these observations were made in a little over two decades since 2000, is most likely due to a combination of enhanced monitoring and an increasingly conducive environment for HAB proliferation. A dominant portion (~88%) of these HABs was caused by dinoflagellates or cyanobacterial species, with the remaining small contributions coming from three other phytoplankton groups: diatoms, raphidophytes, and haptophytes. A more detailed breakdown of many, but not all, of these observations is provided in D'Silva et al.[15] and Thomas et al.[9] Of the few extant marine cyanobacterial genera, HAB events in India have been reported from *Trichodesmium erythraeum*[27] while a few reports in estuarine environments or backwaters also include *Microcystis aeruginosa*, a freshwater species.[17] Figure 1 depicts the organisms/blooms at different spatial scales for the three most commonly occurring species in Indian coastal/inland waters. Figure 2 shows a geographical distribution of all HAB events in India, along with a breakdown of the respective contributing groups and seasonality. While pre-monsoon blooms are typically cyanobacteria-dominated, post-monsoon/winter seasons are primarily composed of dinoflagellate (e.g., *Noctiluca scintillans*) blooms. HAB formation and sustenance in Indian waters are driven by a combination of factors, including nutrient levels, temperature, and salinity variations in the water column, as well as monsoon-influenced biogeochemistry, as has been reported elsewhere.[9,15] Interestingly, the monsoon seasons see relatively lower HAB reports, but this could potentially be explained by lesser sampling efforts and data collection due to rough weather.[15] The states of Kerala, Karnataka, and Tamil Nadu account for ~67% of all HAB reports in Indian waters, potentially due to the existence of research institutes with a focus on HABs locally, a fact discussed later in further detail. While cyanobacteria account for most of the pre-monsoon blooms in Karnataka and Tamil Nadu, Kerala typically experiences dinoflagellate blooms.

FUTURE PERSPECTIVES

Goal 14 of the UNSDG pertains to "Life below water"[34] and is related to aquatic ecosystem conservation, marine pollution reduction, ocean and human health, and the blue economy.[35] Consequently, through the ongoing UN Decade of Ocean Science for Sustainable Development (2021–2030), concerted efforts are underway to develop science- and policy-focused initiatives to achieve these objectives.[36] As one of the world's fastest-growing and top five economies, India has a pivotal role to play in the implementation of the UNSDGs.[37] Scientific monitoring and research on HAB ecology will play a crucial

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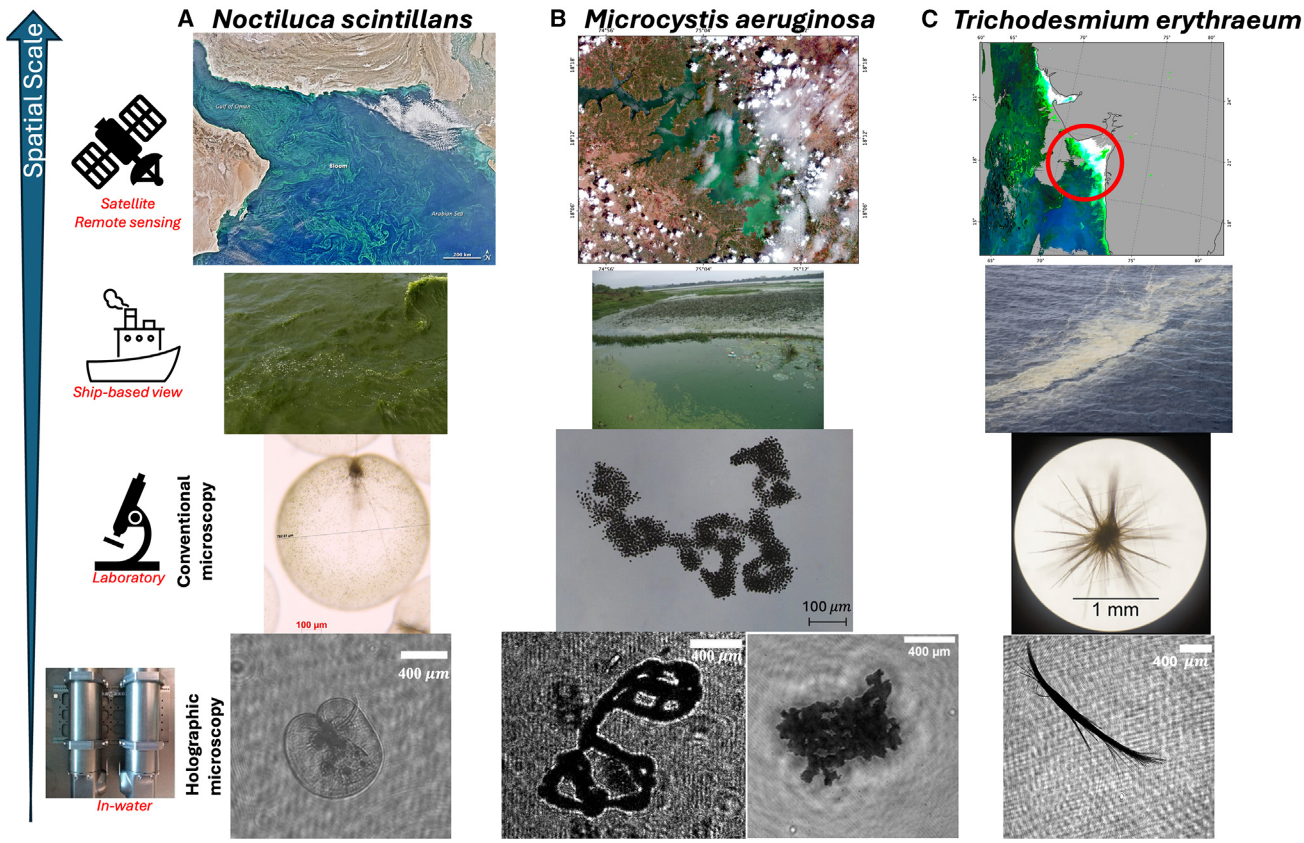

Figure 1. A depiction of three commonly occurring HAB-forming species in Indian waters

(A) The dinoflagellate, *Noctiluca scintillans*.

(B) The freshwater colonial cyanobacteria, *Microcystis aeruginosa*, which is also sometimes found in coastal estuarine waters.

(C) The filamentous marine cyanobacteria, *Trichodesmium erythraeum*.

The top row shows the blooms for each case as seen from satellite imagery; the second panel shows the blooms as observed from a vessel; and the bottom two panels depict individual organisms as observed through traditional and holographic microscopy. (License information: first row: left,[28] middle, and right: Authors of this article made these subfigures. Second row: left: CC-BY license,[29] middle: CC-BY 4.0,[30] right: CC-BY.[31] Third row: left: CC-BY,[29] middle: CC-BY-NC,[32] right: CC-BY,[33] Fourth row: all images are from the lead author's lab.).

role in achieving Goal 14; hence, we focus on outlining potential ideas toward the same in an Indian context below.

In situ and remote sensing technologies for monitoring

Routine surveys and regular research cruises are conducted to monitor plankton community composition, identify HAB events, and enumerate and quantify species abundances. Typically, laboratory-based microscopic analysis of filtered and preserved water samples and the identification and enumeration of different species form the backbone of most of these studies. While these provide valuable information, the process can be manually intensive, laborious, and reliant on the taxonomic expertise of individuals. Semi-automated analysis and benchtop flow cytometric techniques, including commercial imaging cytometers such as the FlowCAM[38] and CytoSense,[39] can alleviate this problem to a certain extent.

In situ imaging sensors

In situ imaging technologies can facilitate plankton characterization in the water column at high spatial and temporal resolutions.[40] Advances in digital cameras and data processing methods have led to rapid growth in the development and deployment of different custom-built and commercial *in situ* imaging sensors for HAB monitoring. Probably the most popular commercially available *in situ* imaging sensor in use today for HAB research is the Imaging FlowCytobot (IFCB),[41] which has been deployed for diverse studies in locations around the world, including the US,[42,43] Europe,[44] and China.[45] Similarly, digital holographic imaging has shown great promise for routine monitoring[46,47] as well as addressing questions related to the ecology of HAB-forming species, based on hitherto hard-to-make *in situ* observations at high spatial resolutions.[48,49] Importantly, the freestream approach and larger sample volumes associated with *in situ* holographic sensors allow for relatively undisturbed measurements of size distributions of colonial plankton.[50] The integration of imaging and other optical sensors on autonomous underwater vehicle (AUV) platforms[51] or tow bodies[47] can greatly enhance spatial coverage to characterize cell abundances and bloom dynamics over large swathes of the water column. In very shallow coastal waters, where AUV operation is difficult,

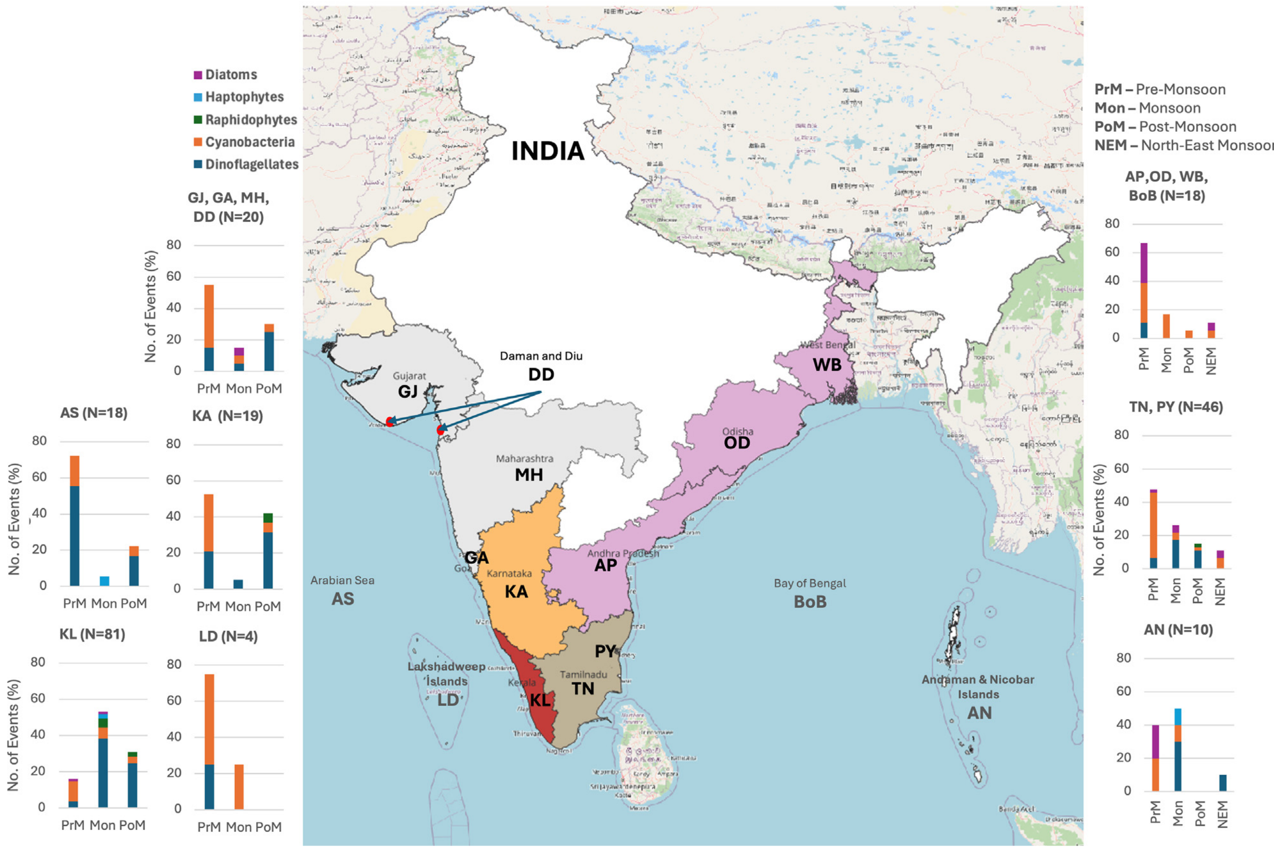

Figure 2. A geographical map of the Indian coastline, showing the location of historical HAB events

Geographically, data are grouped into 8 distinct regions for the West and East coasts respectively: (i) The states of Gujarat (GJ), Maharashtra (MH), Goa (GA) and the Union Territory of Daman and Diu (DD); (ii) Karnataka state (KA); (iii) Kerala (KL); (iv) Offshore waters of the Arabian Sea (AS); (v) The Lakshadweep archipelago (LD); (vi) The state of Tamil Nadu (TN) and the Union Territory of Puducherry (PY); (vii) the states of Andhra Pradesh (AP), Odisha (OD), West Bengal (WB), offshore waters of the Bay of Bengal (BoB) and (viii) Andaman and Nicobar Islands (AN). The number of HAB events in each grouping is represented by N. The colors in the bar charts represent different algal groupings: Dinoflagellates, Cyanobacteria, Haptophytes, Raphidophytes, and Diatoms. The seasons are broken down into pre-monsoon (PrM, Feb–May), southwest monsoon (Mon, Jun–Sep), post-monsoon (PoM, Oct–Jan for West coast and Oct–Nov for East coast), and northeast monsoon (NEM, Dec–Jan, for East coast only). See also the dataset by Kolluru and Nayak[26] for comprehensive details of all known HAB incidents in coastal and estuarine Indian waters. Two of these records are not included in the above figure as either their location or the exact month of the occurrence was not reported.

autonomous sail-powered surface vehicles can be employed. Such a vessel has been successfully deployed previously for monitoring *Karenia brevis* blooms in the Gulf of Mexico[52] using non-imaging approaches; however, integrating *in situ* imaging tools on the platform is feasible.

Significant efforts are currently underway to leverage machine learning based approaches for plankton classification from *in situ* imaging systems.[53,54] For example, method-specific approaches have been developed for imaging flow cytometry[41,43] and holography.[47,55] However, the reliability of these novel methods to generate species-level taxonomic classifications at required accuracies is an open debate.[56] The availability of open-source plankton databases that can be leveraged to develop machine learning (ML) approaches, such as EcoTaxa,[53] Woods Hole Oceanographic Institution (WHOI) plankton database,[57] etc., can play a crucial role in developing more robust and accurate classification schemes. This is especially true for geographical areas with low pre-existing data coverage, where there is a necessity for the development of trustworthy taxonomical databases, which can be facilitated by ensuring easy and open data accessibility and cross-organization coordination. A potential way to achieve this is to mandate open data access for government-funded research.

In situ imaging approaches are not without drawbacks; for example, Indian coastal waters are strongly influenced by freshwater flow from major rivers and sediment run off from land boundaries. As a result, unusually high suspended particulate matter (e.g., Sundarbans- ~700 mg/L[58]) can pose local scale challenges when implementing imaging approaches. Secondly, the main drawback of currently available commercial imaging instruments is the substantial costs associated with the purchase, import, maintenance, software, and servicing of these sensors, which prevents them from being deployed at scale, or in growing economies in the Global South, with limited investments in research and monitoring programs. For example, an IFCB can cost upwards of $150,000, which makes high spatial and temporal coverage across a large geographical area, typically infeasible. Large-scale and continuous plankton sampling requires frugal sensors, facilitating deployments of sensor networks and expanded sampling capabilities. For example, the PlanktoScope provides an open source imaging platform that can be rapidly built and adapted by scientists for plankton imaging,[59] offering an attractive alternative for other benchtop imaging setups. The open-source design facilitates building an affordable sensor (with parts costing < $1,000), while slightly more expensive commercially built versions are also available for purchase. The PlanktoScope is finding increasing use in the plankton observation and algal bloom monitoring community as a valuable substitute for more expensive sensors. More recently, ESPressoscope, a modular platform for different imaging approaches, has been developed and shown to be viable for *in situ* or ship-based monitoring of plankton.[60] From an Indian perspective, a twofold approach with (1) a long-term focus on developing an indigenous ecosystem for advanced sensor development (decadal scale) and (2) a more short-term (2–5 years) effort to target low-cost simple sensor development for deployment at scale would offer a compelling means to tackle this issue.

Remote sensing approaches

Satellite remote sensing for HAB detection and monitoring has been widely adapted over the past few decades.[61,62] The primary advantage of this approach is the ability to image large swaths of the ocean and characterize the spatial and temporal evolution of blooms over hundreds of kilometers. Significant advances in HAB detection and biomass estimation have been achieved with hyperspectral remote sensing data.[61,63,64] However, satellites are limited to characterizing HABs in surface or near-surface waters (<10–15 m); consequently, characterizing the vertical extent of blooms or subsurface thin layers of HAB-forming species is not possible.[65] Additionally, the cell concentrations within a bloom may have to reach or exceed certain thresholds before being detectable through satellites (e.g., 50 cells/mL for *K. brevis*[66]), thus rendering early detection and bloom initiation studies infeasible. Further, the coarse resolution of individual pixels in most satellite images cannot fully resolve finescale features and variations within the bloom. For example, in the case of polar-orbiting satellites like Sentinel-3 Ocean and Land Color Instrument (OLCI) with 1–2 days revisit time, the resolution (~300 m) is too coarse to monitor small water bodies, as well as in resolving fine scale variations within the bloom area. Although some high spatial resolution sensors on different satellites have been used to detect HABs in small waterbodies,[67,68] their revisit times can exceed a week, thus limiting the temporal resolution of the data. In addition, cloud cover can lead to unavailability of data during critical times, e.g., Indian monsoon seasons, which can typically see sustained periods (several days) of cloud cover, inhibiting satellite coverage.[69] There are also challenges associated with studying coastal waters due to interferences from land masses, leading to critical data gaps in sensitive regions, where HABs are initially formed.[70] Despite these limitations, satellite remote sensing can provide valuable information on temporal and spatial evolution of HABs.

Satellite remote sensing has been extensively used by the Indian scientific community to characterize HABs, with reports since the early 2000s.[71] An adapted version of the "red-tide index," developed by Ahn and Shanmugam,[72] is currently used by the Indian National Centre for Ocean Information Services (INCOIS) to obtain a bloom index for regular HAB related monitoring, detailed in a later section. Other bio-optical algorithms for classifying common HAB-forming species (e.g., *Noctiluca scintillans* and *Trichodesmium erythraeum*) in Indian coastal waters using remote sensing data have been successfully developed and implemented.[73] Traditional earth observation satellites require large spacecraft with multiple payloads, escalating costs for design, development, deployment, and maintenance. For example, the SeaWiFS ocean color sensor launch cost > $100 million (Forecast International Report), while the recently launched National Aeronautics and Space Administration (NASA) Plankton, Aerosol, Cloud, and ocean Ecosystem (PACE) satellite mission cost nearly $1 billion. CubeSats—low-cost nano-satellites—offer a more economical approach toward remote sensing; for example, the first CubeSat designed for ocean color measurements in coastal environments, SeaHawk with HawkEye sensor, cost a relatively cheaper $1.7 million for two units.[74,75] HawkEye offers a resolution of ~130 m/pixel and the data are open source. Commercial satellite data providers have launched CubeSats capable of resolving meter-scale features[76]; a public-private partnership with a favorable cost-benefit analysis might provide a means to enhance data coverage for HAB research at high resolutions.[68] Further, synthetic aperture radar (SAR) in combination with optical data has also been used for cyanobacterial bloom detection.[77] However, HAB detection and monitoring using commercial satellite imagery as well as synergistic use of optical and SAR imagery is still in its incipient stage.

Uncrewed aerial vehicles

Uncrewed aerial vehicles (UAVs) offer a complementary approach to satellite imagery and can negate many of these disadvantages. UAVs can be equipped with multiple sensors for efficient monitoring and data collection. They can provide high spatial resolution data at low cost in coastal waters and are not hampered by the presence or absence of clouds. They can also easily be configured for repeated flights over an area, thus allowing for temporal mapping of algal blooms at shorter scales than satellites.[78] Both rotorcraft and fixed wing UAVs have been used, and they each have their own advantages. For example, fixed wing UAVs typically have a longer flight time than rotorcraft UAVs, but rotorcraft UAVs are preferred for closer inspections.[78] Geographic Information System (GIS) mapping from fixed-wing UAVs have been used to identify cyanobacterial mats and estimate their spatial extents.[79] They were also able to discriminate, through image-processing, surface mats from soils and benthic mats at a 20 mm resolution. Flynn and Chapra[80] demonstrated the use of a low-cost (<$1,500) multi-rotor UAV-based aerial imaging system for mapping submerged aquatic vegetation. Even with such an inexpensive system, they were able to get a spatial resolution of 0.25 m and were able to conduct repeat mission. Initial attempts in using UAVs for HAB studies in coastal and inland waters, including the US Great Lakes, have shown significant promise.[52,81,82] However, as UAV-based HAB detection and identification is still very much in its nascent phase, significant progress is still required, including development of standard protocols, sampling strategies, cross-validation, etc.

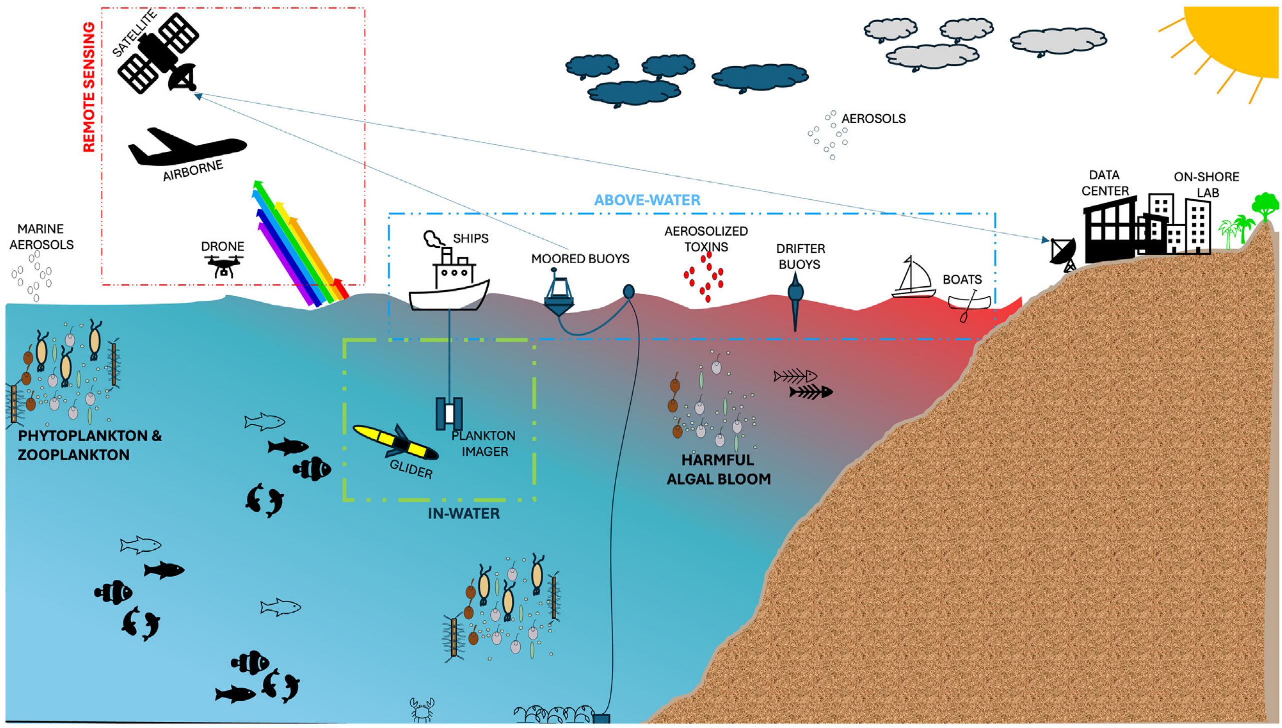

Figure 3. A schematic depicting a potential HAB observation network that utilizes a holistic approach by combining different complementary technologies that enable synoptic observations of a bloom across different temporal and spatial scales

Overall, a "horses for courses" approach or an integrated monitoring framework, where diverse technologies and monitoring approaches are leveraged to generate a holistic sampling protocol (Figure 3), might greatly benefit HAB research and monitoring in India moving forward.

Integrated monitoring networks, early warning systems and HAB databases

Detailed observations of bloom formation, sustenance, and dissipation, across different spatial and temporal scales are crucial in both routine monitoring and development of a solid scientific understanding of species' ecology and contributing factors, which can facilitate mitigation and prevention efforts. The development of operational coastal observation networks and early warning systems (EWS) represents a two-pronged approach to tackle HAB issues. Leveraging existing infrastructure and adding new technologies, along with efficient data management, processing, and dissemination are key elements of a functional HAB observation network.[83] Several countries or regions have mature monitoring networks for sustained HAB observations, with varying levels of investment and focus areas; for example, some countries have a comprehensive set of data and parameters assessed in their networks, while others have a much narrower mandate, with particular focus on HABs from the context of biotoxin monitoring, seafood safety and health. The United States Integrated Ocean Observing System (IOOS) is a good example of an integrated coastal observation network across the country's vast coastlines. It consists of eleven different regional associations (RAs), geographically representing the Pacific, Atlantic, and Gulf of Mexico coastlines, as well as the Great Lakes, Alaska, and the Pacific Islands.[84] The integrated observations are then synthesized into end products for stakeholders as well as used to drive policy decisions. A portion of the IOOS effort is focused on HAB observing capacity-building and strategy-building initiatives through the National Harmful Algal Bloom Observation Network (NHABON[85]). Project PRIMROSE (predicting risk and impact of harmful events on the aquaculture sector) is an European Union initiative, that led to the development of HAB EWS in partner countries, integrating data workflows from existing local HAB/toxin monitoring efforts.[51] France has a long-term phycotoxin monitoring system (REPHYTOX), consisting of 116 stations, spanning the full extent of the country's coastline, providing valuable information on harmful taxa and seafood toxicity across several decades.[86] Among Asian countries (excluding India), HAB research has been primarily driven by China, South Korea, and Japan.[87–89] Enhanced anthropogenic stressing of aquatic ecosystems, at least in part due to the unfettered economic growth in China during the 1990s and 2000s, has been linked to increased HAB occurrences. This issue, coupled with enhanced investment in scientific research, has led to substantial development and expansion of HAB monitoring networks and mitigation initiatives in HAB hotspots in the country.[88] HAB monitoring programs also exist across other countries or regions, e.g., Latin America and the Caribbean[90] and New Zealand.[91]

Considering the case of India, if the HAB distribution map (from Figure 1) is overlaid on a map of oceanographic research institutes in the country, there is a striking correlation, indicating that the data sampling at specific locations might well be causing a knowledge bias. Indeed, most of the HAB observations are around Chennai, Kochi, Mangaluru, and Goa, where the said institutions are located, highlighting the patchiness in HAB sampling in Indian waters as observed by Bhat and Matondkar.[16] This lends further credence to the urgent need to establish a comprehensive monitoring program that covers most of the extant Indian coastal range.

Currently, in India, there are examples of routine HAB or water quality monitoring programs, but these are scattered between multiple institutes and agencies. For example, Mumbai port and adjacent areas have been previously monitored for various HAB species through a pilot initiative initiated by the Global Ballast Water Management Program.[92] National Center for Coastal Research (NCCR) and INCOIS operate several buoys and monitor water quality in the Arabian Sea and the Bay of Bengal.[93,94] Typically, assorted sensors for phytoplankton pigment assessment (e.g., chlorophyll, phycocyanin, and phycoerythrin) are deployed along with nutrient monitoring sensors. A multi-national HAB research program with the Center for Marine Living Resources and Ecology (CMLRE), Kochi, as project coordinator, along with various participating institutes has been initiated by the MoES. Through this program, various HAB aspects like open ocean HAB dynamics, toxicology, coastal HABs, HAB retrieval algorithms, and modeling are studied.[15] A coordinated and coherent strategy for establishing a national network of coastal observations, with a specific focus on HABs, is a critical need, also highlighted in earlier works.[16]

Similarly, there is also a need to establish HAB EWS, which can be especially useful to aquaculture and fisheries industries, coastal residents as well as recreational users of water bodies. An early alert of a HAB incident can enable aquaculture farms to appropriately tune harvesting schedules or plan temporary shutdown of operations, potentially avoiding or alleviating financial losses.[95] Satellite remote sensing tools offer a useful means to establish bloom extent and estimate if cell concentrations are exceeding set thresholds. For example, CyanoTracker is a cloud-based architecture developed for global observation of cyanobacteria blooms. It uses information from different sources, including satellites, social media, and *in situ* sensors, to integrate information to produce spatial maps disseminated through a dedicated website, social media, and directly to appropriate agencies to issue time-sensitive real-time warnings.[96] For inland waters, the innovative CyanoKhoj service, an adaptation of the CyanoTracker program based on the Google Earth Engine for tracking cyanobacterial blooms, has been developed.[97] In India, INCOIS' Algal Bloom Information Service (ABIS) is equipped to provide bloom alerts in four coastal and offshore hotspots, namely Kochi, Gulf of Mannar, Northeast Arabian Sea, and off Gopalpur in the coastal Bay of Bengal.[98] The bloom index indicates the presence or absence of a bloom based on a threshold value. For each of the monitored regions, average and standard deviation of the bloom index is provided as maps. In addition to the bloom index, a suite of parameters including chlorophyll, sea surface temperature, spread of green or red *Noctiluca*, abundance of pico, nano and micro phytoplankton etc., are also provided. Alerts are generated with three different types of indicators—"normal," "watch," or "warning," based on the reported index values. For example, if a particular sector of a satellite image has more than half or three-quarter of the pixels exceeding bloom threshold values, the area is delineated to be under an algal bloom "watch" or "warning," respectively.[99] The integration of novel *in situ* imaging technologies in HAB EWS has great potential, including earlier detections of bloom inception than satellite data can provide. Bottlenecks associated with real-time data processing onboard the sensor and data transmission are ongoing challenges that require working on; this can be facilitated by directing funds for developing these technologies further.[70]

Databases with detailed information on past and ongoing HAB events are extremely crucial to develop an understanding of spatial and temporal trends as well as mechanisms and contributors to bloom initiation, formation, and sustenance. They can also play an important role in mitigation efforts. The United Nations Educational, Scientific and Cultural Organization (UNESCO)'s Intergovernmental Oceanographic Commission (IOC) hosts the Harmful Algal Event Database (HAEDAT, https://haedat.iode.org/), in coordination with the International Council for Exploration of the Sea (ICES) and the North Pacific Marine Science Organization (PICES). Events that are entered into the database are carefully curated to meet one or more relevant criteria for qualification as a HAB, e.g., seafood toxin accumulation, visible color changes in the water mass, etc., spanning the freshwater to marine continuum.[100] While the initial reports mainly focused on the North Atlantic (ICES) and North Pacific (PICES), regional networks in other geographic locations around the world now contribute to this growing database. As of November 19, 2024, a total of 21,971 events across 106 countries (including overseas protectorates or departments, e.g., Mayotte and La Reunion), have been logged in HAEDAT; yet only 29 of these reports (~0.13% of total) are from Indian waters (including 3 freshwater cyanobacterial reports). These records comprise of only ~13% of the 218 HAB events reported across historical datasets in India.[26] While noting that some of these might not meet the HAEDAT criteria to be listed there, the low percentage of these reported, highlight the fact that proper documentation of Indian HABs in international databases is a crucial element that needs to be tackled effectively moving forward, to ensure proper representation in global HAB studies.

Human health effects and clinical studies

Different HAB-forming species can generate a diverse range of potent toxins, leading to an array of potential effects on humans.[101] The bioaccumulation of these toxins through the aquatic food web[102] and consequent seafood consumption by humans leads to at least five commonly documented types of seafood intoxications,[101] including diarrhetic, paralytic, neurotoxic, and amnesic shellfish poisoning.[103–106] Aerosolization of some toxins, e.g., brevetoxin, generated by *K. brevis*, can lead to respiratory illness in humans,[107] whereas other toxins, such as microcystin, can cause ill effects based on skin contact or ingestion while recreating in or drinking from affected water sources.[100] Globally, many HAB detection and monitoring programs are in fact directly couple with and driven by the need to protect commercial fisheries and aquaculture industry.[7] Extensive and careful monitoring of commercial shellfish has alleviated the impacts on human health through consumption, but a lot remains to be known about the other forms. Further, while short-term health effects are well documented, long-term exposure to toxins from recurring and persistent HAB events has been much less studied.[108] It is also important to establish safety guidelines associated with thresholds of exposure and consumption of potentially affected seafood.[109]

India is the second largest contributor to fisheries and aquaculture production in the world, with an estimated total output of 17.5 million tons in 2023 and aquaculture alone contributing to 13.4 million tons. The exports of fish and fishery products generated a revenue of USD 7.38 billion in 2023.[110–112] The effect of HABs on human and marine ecosystem health has received scant attention in India. Only sporadic reports of human illnesses and fatalities specifically attributed to HAB incidents exist. For example, incidents of paralytic shellfish poisoning (PSP) due to mussel consumption have been reported in several states; however, the causative organism was not definitively identified.[16,113] Given the fact that water-borne diseases affect millions of people and lead to substantial fatalities[114] every year, there is a strong possibility that some of these might be associated with HAB species in inland and coastal waterbodies. Carefully designed human health studies, especially in areas with known HAB incidents, should be conducted to accurately assess the impact of HABs on human health and associated economic costs. Various quantitative studies have reported significant economic losses associated with HAB-related illnesses, including hospital visits, in-patient costs, and absence-related work costs,[106,115,116] but such a detailed study is lacking in the Indian context.

Routine monitoring programs should include the following to provide a comprehensive view of HAB events and associated risks: (1) establishment of species-specific safety thresholds in organism abundances for HAB-forming species; (2) monitoring toxins in seafood and especially shellfish, to alert the public and temporarily halt consumption until safe to resume; and (3) careful documentation of human health effects and hospital visits in affected regions. This requires a combined interdisciplinary effort between ocean and human health experts including scientists and doctors.

Public outreach to enhance awareness and policy-driven changes

Establishing an integrated framework at the nexus between science, society and policy is a necessity for tackling HAB issues in India. At both local and national scales, HAB-focused initiatives need to be integrated with coastal ecological health monitoring and for wider consequences for blue economy. The most successful example of driving policy changes to facilitate HAB research and monitoring is the US Congress' authorization of the Harmful Algal Bloom and Hypoxia Research and Control Act (HABHRCA) in 1998,[117] which mandated federal investments in HAB research, control, and monitoring. The cascading effect it has had on public awareness and scientific research, and responses to HAB events in the US cannot be overstated. Similar initiatives are required for India.

Indian public awareness on water quality issues is significantly lacking. Public outreach, training the Science, Technology, Engineering, and Mathematics (STEM) task force, and citizen science initiatives by governmental institutions and scientists can play an important role in alleviating this issue. A few existing programs are listed below. INCOIS conducts training programs for students, research scholars, and early career professionals through the International Training Centre for Operational Oceanography initiative, which helps build human resources in this research area. INCOIS leads initiatives where a science team visits coastal regions for validation of satellite products and conducts local community interactions, including training fisherfolk on available tools.[118–121] Further, INCOIS has already developed a mobile application, Smart Access to Marine Users for Data Resources, and ocean Advisories (SAMUDRA), targeted toward stakeholders such as fishermen, that provides updates on potential fishing zones, ocean state forecasts, tsunami warnings, etc. Building off the base application to include HAB alerts could be considered in the future. More broadly, focusing and initiating activities such as the training of trainers (ToT) through which the wider implications of HAB can be communicated more effectively to local communities would be beneficial.

Engaging coastal residents and regular seafaring groups (e.g., fisherfolk), who are important stakeholders in citizen science initiatives, is yet another means of increasing awareness. The HABscope, a low-cost microscope, is one such successful example[122] that has been used to gather valuable data on "red tide" (*K. brevis*) blooms in the coastal Gulf of Mexico in Florida. Paired with a cell phone, HABscope data are recorded and uploaded to a server, where the videos are processed to obtain *K. brevis* cell counts. Citizen scientists identified through extended networks are chosen depending on availability and proximity to coastal areas with bloom prospects or ongoing events. Extensive training including through a user manual containing step-by-step instructions on HABscope usage is provided to the volunteers. At least one water sample and an associated video record through the HABscope is uploaded to the cloud for data processing by each volunteer. The number of samples uploaded by the volunteers is used to assess their ability for regular sampling. The outcomes of the initial study indicate that the samples collected by the volunteers with training provide desirable results, i.e., the correct category of cell concentration during a bloom. The mass deployment of the HABscope during ongoing red tide blooms by these volunteer citizen scientists thus adds valuable spatial and temporal data to our understanding of bloom dynamics; the tremendous success of this program has resulted in the development of a second version of the instrument to enhance and streamline these monitoring efforts in the future.[123] The successful adaptation of the FoldScope,[124] a low-cost paper microscope for citizen engagement and STEM education in India,[125] through support from the Department of Biotechnology by the Indian government is a good precedent; envisioning a similar initiative surrounding HABs in coastal areas holds substantial promise.

DATA AND CODE AVAILABILITY

The list of HAB events in Indian waters and associated details are available on Zenodo.[26]

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AUTHOR CONTRIBUTIONS

A.R.N. and A.K. conceived the idea for the review article. A.R.N. and S.K. contributed equally to researching the literature and writing the first draft as well as revisions of the manuscript. All authors contributed to editing and approved the final version.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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